

# A Roadmap for Aircraft Engine Life Extending Control

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## Abstract

The concept of Aircraft Engine Life Extending Control is introduced. A brief description of the tradeoffs between performance and engine life are first explained. The overall goal of the life extending controller is to reduce the engine operating cost by extending the on-wing engine life while improving operational safety. The research results for NASA's Rocket Engine life extending control program are also briefly described. Major building blocks of the Engine Life Extending Control architecture are examined. These blocks include: life prediction models, engine operation models, stress and thermal analysis tools, control schemes, and intelligent control systems. The technology areas that would likely impact the successful implementation of an aircraft engine life extending control are also briefly described. Near, intermediate, and long term goals of NASA's activities are also presented.

## 1. Introduction

Current aircraft engine controllers are designed and operated to provide both performance and stability margins. NASA Glenn Research Center and its industrial and academic partners have been working together toward a new control concept that will include the consideration of engine life usage to minimize overall operating costs. The new controller design will utilize damage models to monitor the damage rate and damage accumulation of critical parts. The tradeoffs between performance and structural durability may be assessed for different levels of mission requirements and engine life states. The goal of the proposed controller is to reduce engine operating costs while improving operational safety.

This paper will then present a roadmap for the life extending control program for aircraft engines. The building blocks required for a successful program include a high-fidelity engine operating model, temperature/stress models for life-limited components, life models for life-limited components, mission profiles, sensors, real-time life tracking, advanced actuation, and optimum control for the integrated system. Details of each block will be discussed including technology readiness, implementation issues, and optimum control integration.

## 2. Elements of Engine Life Extending Control

The Life Extending Control (LEC) concept was first introduced by Lorenzo et al. in the early 90s [1,2]. It was first applied to a simulation of the Space Shuttle Main Engine (SSME). The open loop and closed loop applications of LEC were successfully demonstrated. A two-tier controller architecture was proposed for the LEC

system, which consisted of a linear performance controller in the inner loop and a nonlinear damage controller in the outer loop. The simulated LEC was able to reduce the transient damage in the turbine blades of one of the high-pressure turbo pumps by a factor of 35 while keeping the transient performance degradation very small [3,4,5]. The main elements of Life Extending Control application to air-breathing propulsion system are illustrated in Figure 1 and discussed in the following subsections.

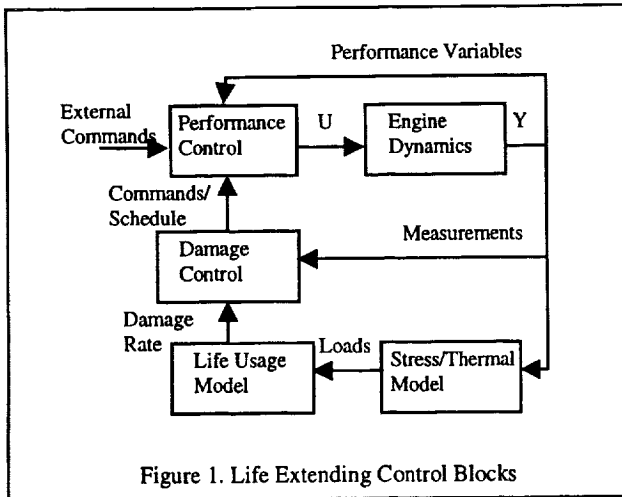
### Life Usage Model

The calculation of the life of the engine components is the centerpiece of Life Extending Control. Generally speaking, current engine component life is calculated during the engine design phase. During the engine design, each engine part has to be analyzed using the maximum rated engine operating conditions. Although there are many parts with many different failure modes to be considered, the most important life-limited parts are the rotating components in the hot section directly after the burner. The typical failure modes for the hot section engine components are low cycle fatigue (LCF), thermo-mechanical fatigue (TMF), and creep/rupture. Most of the lifing models are based on fracture mechanics and fatigue crack propagation, which take into account the material properties and the thermal stresses of the engine components [3]. However, for safety reasons, the certified useful life of an engine component is set to be well before a crack would usually occur. This overly conservative life limit recommendation practice has resulted in engine parts being removed without evidence of degradation, wasting remaining usable life.

More accurate lifing calculations of each component are needed to enable the implementation of LEC. Actually, better lifing calculations and life tracking will also improve the operational safety of the engine. It is necessary to have the engine life calculated during engine operation and updated for every major cycle. An ideal lifing model for LEC will be a package including the lifing calculations of all critical failure modes of all life-limited components. It will be calculated in real-time during engine operation and after each thermal stress cycle according to the operating conditions of the engine. The capability of tracking component life usage is also important because used parts with substantial life (time) left are often re-used during the engine overhaul process. And, because the component life (usage) cannot be measured directly, it is also very important to have the lifing model verified experimentally (by factory

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endurance testing) or empirically (through the study of field engine maintenance data).



### Engine Model

In order to calculate the life usage of an engine component, it is necessary to obtain the operating conditions of the component. This can be accomplished by either direct sensor measurements or by an on-board engine model simulation. Since the engine sensors are designed for control and safety monitoring purposes, they can only provide very limited information for engine life calculations. During the design phase of an engine, an engine cycle model ("deck") can be used to determine the engine component conditions during different flight scenarios. The cycle deck models the engine with component efficiencies and performance maps as well as basic physics and is validated through various engine and flight tests. It provides a set of gaspath pressures, temperatures, and shaft speeds for each mission point in the flight profile under different ambient conditions. While it is adequate to use a cycle deck to predict the operating conditions of engine components, there are some shortfalls when applying it to life extending control. First, the cycle deck is inherently large and it may not be feasible to run in a life extending control algorithm where real-time computation may be necessary. Second, although the cycle model provides good overall simulation accuracy, it may not be detailed enough at the locations that are critical for engine life calculation.

An ideal engine model for life extending control is a simplified engine model that can give a fast but accurate overall engine operation results for both steady-state and transient conditions. It shall also have the capability to update engine performance to account for degradation based on the sensor measurements. And, for each life-limited component of interest a detailed model will be used to provide the additional variables required for life usage estimation.

### Stress and Thermal Analysis

Stress and thermal analysis is the tool bridging the gap between measured operating variables and life models. Usually, engine sensors and the on-board model are able to provide values for rotor speeds, temperature, and pressure at select points. However, the life calculation requires much more detailed information including metal temperature, temperature gradient, mechanical load, and stress at each critical location on the part. Engine companies usually use tools such as finite-element analysis (FEA) to calculate the thermal and stress conditions. Together with other variables such as shaft speeds, material properties and component geometries, further analysis is also done to determine the loads and stresses of all possible failure locations at various operating conditions. This information is then used to predict the life of engine components.

In Life Extending Control, it is unrealistic to use finite element analysis for the stress and thermal analysis for an on-line application. This part of the calculation can be combined with the life model so that life usage can be calculated directly from the engine parameters. It may also require a lot of model simplification and linearization in this process to increase the execution speed while preserving the fidelity of the life model.

### Possible Control Schemes

There are several control schemes that have the potential of increasing the life of an aircraft engine. Each control scheme requires extensive study of its potential effect, sensor and actuator requirements, and implementation integration with the current control algorithm.

A life extending control scheme that requires no engine modification is acceleration and deceleration logic modification. During acceleration and deceleration, temperature gradients of many life-limited components will build up. Thermo-mechanical fatigue (TMF) and low cycle fatigue (LCF) are functions of both temperature gradients and absolute metal temperatures. Also, metal surface delamination is believed to be a strong function of the temperature gradient. It is possible to shape the acceleration and deceleration schedule of an engine to minimize absolute metal temperatures and temperature gradients (and thus damage) while still meeting the performance requirement of the engine [4].

Another control scheme that does not require a hardware modification is model based adaptive control to optimize engine operation at cruise, taking into account cruise time, fuel consumption, and rupture/creep life of turbine blades. In an ideal situation, the engine model should be such that it can be updated frequently to match the operation of the deteriorated engine. This control scheme will be used primary for the off-line flight path planning for establishing the cruise condition. Because of the long duration of the cruise time, the potential benefit

in terms of engine life and fuel consumption can be very large while the control scheme is relatively easy to implement.

Since the life of an engine is directly related to the component metal temperature, it is safe to assume that a properly modulated cooling and heating system will be able to reduce component life consumption by reducing both the absolute temperature and the temperature gradient of critical parts. However, a modulated cooling/heating system requires some hardware redesign to increase the cooling air capability and actuators that can respond to the controller's request.

An active clearance control (ACC) system can also potentially save engine on-wing life by tightly controlling the blade tip clearance. The tip clearance control can improve the life consumption by reducing rubbing and by maintaining the engine operation close to the design temperature even when the engine starts to deteriorate. The main obstacle to implementing a closed-loop ACC system is the lack of proper tip clearance sensors and rapid response actuators.

#### Controller Architecture

The basic concept of life extending control is to adjust the operational settings to minimize damage to critical components while achieving acceptable dynamic performance of the plant. It should be emphasized that a fundamental tradeoff exists between the level of achievable performance and the ability to extend the life of system components generating that performance. In designing a life extending control system the following constraints must be considered:

- The life usage of a component cannot be measured. It has to be calculated using a life model along with measurable engine variables such as temperature, pressure, and time. The life model is usually obtained using experimental data and the prediction is probabilistic in nature.
- The acceleration and deceleration performance requirements of an engine are usually established under a very strict guideline set by the FAA.
- There are many life-limited parts in an engine and each typically has several critical failure modes. Furthermore, the damage states of all parts involved need to be monitored and taken into account in the optimization process. Also, engine maintenance practices, such as when to overhaul an engine and under what conditions the used parts are salvaged, play an important role in defining what is optimum in the control algorithm.
- Different stages of engine operation have different effects on life consumption. For example, during the cruise condition rupture/creep is the main concern and the absolute metal temperature will be used to calculate the life usage of an engine part at cruise. Low cycle fatigue (LCF) and thermo-mechanical fatigue (TMF) are determined mainly by the engine

acceleration and deceleration cycles and temperature gradients of engine parts.

A multi-level life extending control system is illustrated in Figure 2. The proposed control architecture has three levels of decision and control. The traditional tracking control of engine performance is accomplished at the lower *Execution Level*. This level of control is executed in real-time. The *Coordination Level* evaluates the current health condition of the engine and engine components, monitors the performance, and performs an on-line optimization according to the gathered information. This level of control is executed on-line but not necessarily in real-time. The highest level is the *Supervisory Level*, which is a discrete-event driven process. The supervisory control modes are determined according to the external commands and the status of engine health and performance conditions. The rationale for this approach is that the life extending control is a combination of continuous monitoring and discrete decision-making processes.

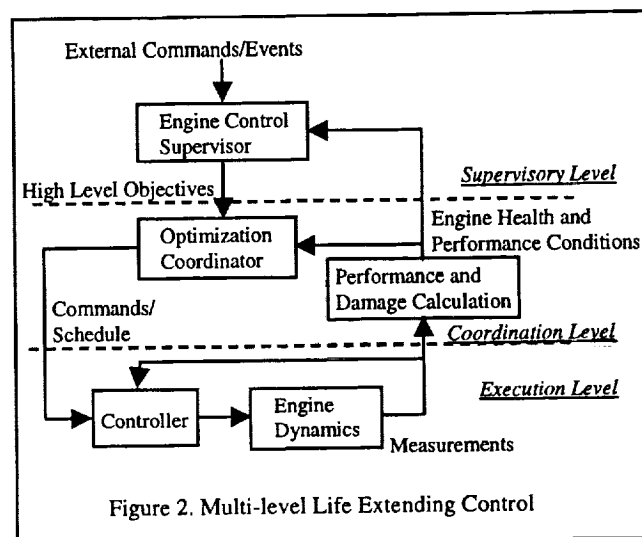


Figure 2. Multi-level Life Extending Control

### 3. Technology Road Map for LEC

The technology areas that can have impacts on the successful implementation of aircraft engine life extending control are summarized below. These technologies are classified into the following three time frames:

Near term (3-5 years): Technologies that do not require a hardware change of current engine systems are generally easier to implement and gain acceptance. Improvement in computational power can also be a factor in LEC implementation.

- *Improved engine life model and tracking:* An ideal engine life model will include models of all critical components. Each component life model can be calculated using measurable engine variables. All life

models are verified experimentally, and their stochastic characteristics are established.

- *Modified accel and decel schedules:* Accel and decel schedules can be modified to minimize the temperature gradients and thermal stresses of life limited components while meeting the defined performance requirements.
- *On-line engine model:* An on-line engine model that can track engine performance and degradation is especially important for both LEC and health monitoring purposes. It can provide better calibrations to the life calculation for degraded engines, which are usually at the end stage of their usable life. It can also provide more accurate optimization settings for the cruise conditions for LEC.
- *Integrated control system for engine health management:* To implement the proposed multi-level life extending control system under the given constraints is a challenge. A detailed design of how to carry out the defined functions and how to resolve the inherent multi-objective optimization problem is required at this stage.

Intermediate term (5-10 years): There are several technology areas that are on the verge of a breakthrough and are very promising for LEC applications. This group requires small modifications to the engine.

- *Sensors for life prediction:* Although a direct life measurement is not feasible, it is possible to develop sensors that will bring the life calculation closer to the feedback loop. These sensors include crack detection and measurement sensors, stress measurement sensors, and tip clearance sensors. All these sensors must be capable of operating under harsh engine conditions.
- *Improved active clearance controls:* An improved active clearance control (ACC) system has the potential of reducing wear, improving specific fuel consumption (SFC), reducing temperatures, and extending life by well controlled transient and steady state clearances during operation. In addition to the tip clearance sensors, a new actuator system for a rapid response tip clearance control is also needed.

Long term (10 or more years): Some prospective LEC technologies require major design changes of engines.

- *Flexible engine cooling/heating:* Engine component life can benefit from extra control authority such as actuators for extra cooling/heating modulation, and extra engine bleed capability to shift operating conditions.
- *Designing for LEC control:* It is possible to design an engine with the consideration of overall cost including control and maintenance. During the design phase of

an engine, life of a component will not only be calculated, but it will also be analyzed for possible damage reduction and to ensure that adequate control accommodation authority is provided.

Current NASA activities on LEC include a short-term study program led by Scientific Monitoring, Inc. (SMI) and Honeywell that is concentrating on the near term implementation of LEC for the current engine configuration [6]. This program is implementing smart accel/decel schedules to minimize the peak temperature and temperature gradient to minimize damages. Under another NASA contract, GE Aircraft Engine (GEAE) has completed a trade study to evaluate potential LEC schemes for long-term objectives [7]. Controller architecture and control algorithm studies are being done through in-house research as well as university grants, on-site research fellowships, and summer fellowships.

#### 4. Conclusions

The concept of Aircraft Engine Life Extending Control is described. Elements of LEC are discussed in detail. Technology research areas that may have major impacts on LEC are also classified according to their readiness level for implementation. In summary, the Aircraft Engine Life Extending Control is a high pay-off technology area that is in its early stage. Interdisciplinary research is required to make this technology applicable to aircraft engines.

#### References

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